

# Spectral energy distributions and high-energy emission of BL Lac type objects

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## ABSTRACT

Based on identifications from the Véron and Quasars.org catalogs, we determine the optical-to-X-ray spectral indices for a sample of 201 BL Lac type objects (BLLs) and search for trends in the distribution of these indices of the sources detected in high-energy bands. We find that EGRET-detected sources are low-energy peaked and that the positional correlation with the arrival directions of ultra-high-energy cosmic rays from the previously studied AGASA, Yakutsk and High Resolution Fly’s Eye samples is dominated by low-energy-peaked BLLs.

**Key words:** galaxies: BL Lacertae objects: general – gamma-rays: theory – acceleration of particles.

## 1 INTRODUCTION

BL Lac type objects (hereafter BLLs) attract considerable attention of both astrophysicists and particle physicists. Among other reasons, it is caused by observation of very-high-energy ( $\sim 1$  TeV) gamma rays from these sources (see e.g. Aharonian (2000); Wagner (2007) and references therein) and by claims for potential association of BLLs with ultra-high-energy (UHE;  $\gtrsim 10^{19}$  eV) cosmic rays (CRs) (Tinyakov & Tkachev 2001, 2002; Gorbunov et al. 2002, 2004; Abbasi et al. 2006). Most probably, only particular subclasses of BLLs are responsible for these high-energy emissions. More precise determination of these subclasses may shed light on the intrinsic mechanisms of particle acceleration in blazars and may help in determination of potential sources yet unobserved at high or ultra-high energies.

Broadband spectral energy distributions (SEDs) of BLLs are known to have a very specific non-thermal two-bump shape. In a popular model, the two bumps are caused by the synchrotron and inverse-Compton radiations (see e.g. Maraschi, Ghisellini & Celotti (1992); Sikora, Begelman & Rees (1994)). Their origin is attributed to other mechanisms in some models (see e.g. Mannheim (1993)). While the overall two-bump shape is quite common, the location of the peaks varies strongly from source to source. In particular, the well-measured low-energy peak corresponds to infrared or optical frequencies in the so-called low-energy-peaked BLLs (LBLs) and to X-ray frequencies in the high-energy-peaked objects (HBLs). As it has been recently understood, intermediate cases are also present. The correlation of the peak position with the intrinsic power of the object (Fossati et al. 1998) is currently under discussion

(see e.g. Padovani (2007)). The second, often worse measured peak is located in the gamma-ray band (MeV to GeV in LBLs and hundreds of GeV in HBLs).

Since LBLs are bright in the optical band and relatively faint in X rays (keV frequencies correspond to a dip between two peaks in this case) while HBLs peak in the X-ray band, the optical-to-X-ray broadband spectral index  $\alpha_{\text{OX}}$  provides a good measure of the position of the first peak in SED (see e.g. Donato et al. (2001)). Detailed measurements of the SED are available for a small fraction of BLLs while to know  $\alpha_{\text{OX}}$  one needs only optical and X-ray measurements performed for a much wider sample of sources. In this note, we use  $\alpha_{\text{OX}}$  as the quantity which characterizes the SED of a BLL; results of a more detailed multiwavelength study will be reported elsewhere. We determine  $\alpha_{\text{OX}}$  for a large sample of BLLs and look for a correlation between the index and the high-energy emissivity of a source. We will see that EGRET-detected sources are mostly LBLs. One of the primary goals of this study is to specify the class of BLLs which correlate with the arrival directions of ultra-high-energy cosmic rays; we will see that the correlations observed previously are also saturated by LBLs.

The rest of the Letter is organized as follows. In Sec. 2, the sample of BLLs is discussed and the index  $\alpha_{\text{OX}}$  is determined. In Sec. 3, we demonstrate the trends in the distribution of  $\alpha_{\text{OX}}$  of EGRET sources. In Sec. 4, we briefly review previously reported UHECR – BL Lac correlation and discuss the distribution of  $\alpha_{\text{OX}}$  of correlated objects. Brief conclusions are summarized in Sec. 5.

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## 2 THE SAMPLE

We study objects classified as confirmed BLLs (class BL or HP) in Véron-Cetty & Véron (2003) (hereafter the Véron catalog). Objects from this catalog were searched for X-ray identifications in ROSAT data in the Quasars.org catalog (Flesch & Hardcastle 2004). There, the Véron objects have been cross-correlated with various published ROSAT catalogs (Voges et al. (1999, 2000); ROSAT (2000b,a); White, Giommi & Angelini (2000)) and the probability of the true identification was presented for each case. Of the sources from different catalogs associated with a given BLL, we select one with the highest probability; we drop the source from the sample if this probability is below 68%. In such a way, we obtain a sample of 201 objects with *V*-band magnitudes given in the Véron catalog and X-ray identifications with one of the ROSAT catalogs. We note that in some cases, the name of the object in the Véron catalog has the ROSAT prefix but this identification has very low probability according to Quasars.org and the corresponding BLL was therefore dropped from the sample.

For the objects identified with the ROSAT latest PSPC catalogs (Voges et al. 1999, 2000; ROSAT 2000b), we calculate the flux in (0.1 ÷ 2.4) keV band from the count rate and the hardness ratio following Voges et al. (1999). In a few cases when the best identification is with the catalog of White, Giommi & Angelini (1994, 2000), we take the flux value presented there. If the object was observed by the high-resolution imager (HRI), the best identification is often with the catalog of ROSAT (2000a); we use the flux values given in the BMW catalog (Panzera et al. 2003) in these cases. These latter fluxes correspond to the same energy band and assume a Crab-like spectrum for each source. It is a relatively rough approximation caused by a poor spectral sensitivity of HRI; however, for firm identifications, the BMW and PSPC fluxes are well correlated.

For each object in the sample, we calculate the optical-to-X-ray spectral index  $\alpha_{\text{OX}}$  using the textbook definition (Carroll & Ostlie 2007),

$$\frac{F_{\text{O}}}{F_{\text{X}}} = \left( \frac{\nu_{\text{O}}}{\nu_{\text{X}}} \right)^{-\alpha_{\text{OX}}},$$

where  $F_i d\nu_i$  is the amount of energy with frequencies between  $\nu_i$  and  $\nu_i + d\nu_i$  per unit area per second, observed by a detector aimed at the source and measured e.g. in W/(cm<sup>2</sup>·s); index  $i$  stands here for either *V*-band,  $i=\text{O}$ , or X-ray band,  $i=\text{X}$ , frequencies and fluxes.

Most of the BLLs are strongly variable at all wavelengths and therefore the use of non-simultaneous observations may introduce random errors as large as 0.3 to  $\alpha_{\text{OX}}$ . Given the fact that the X-ray sample is essentially flux-limited, these errors may be asymmetric for faint objects.

An important correction to *V* and therefore to  $\alpha_{\text{OX}}$  may arise from the contribution of the host galaxy emission. We use the magnitudes from the Véron catalog which are not corrected for the contribution of the host galaxies. These corrections might cause significant systematic errors in  $\alpha_{\text{OX}}$  given the fact that the host galaxy contribution is more important in the visible light than in X rays. The effect of this correction is stronger in fainter, less beamed or misaligned BLLs. Account of this correction on the case-by-case basis would result in a significant reduction of the statistics since

for many objects in the sample (notably for those associated with EGRET sources or correlated with UHECR) the host galaxy was not detected, indicating either powerful or well beamed source. Another approach is to use infrared colour indices to estimate, on a statistical basis, whether the contribution of a host galaxy is important. Developed by Glass (1981), this approach was systematically applied to Véron BLLs by Chen, Fu & Gao (2005), where *J*, *H* and *K* magnitudes were obtained from the 2MASS survey and the objects for which a significant contribution of the host galaxy is expected were determined. To estimate the effect of the contamination by the emission of the host galaxies on our results, we removed these objects (37 out of 201) from our sample and checked that the effects we advocate are present in the reduced sample as well<sup>1</sup>, see below. Since the starlight of the host galaxy is expected to peak in the infrared (see e.g. discussion in Kotilainen, Falomo & Scarpa (1998)), the effect in the *V*-band should be even smaller.

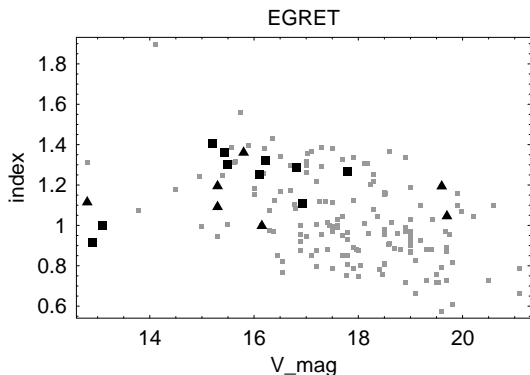
Our sample is derived from the Véron catalog which is incomplete. Therefore, the results of the study may be biased; it is not guaranteed that they are generic and hold for all BLLs in the Universe. However, by comparing different subsets of one and the same catalog, we partially remove the effects of the incompleteness and reveal important trends which can be tested in future studies. Though the selection effects may be different for different subsamples, the most important of them are under control in the present study.

## 3 GAMMA-RAY EMITTERS

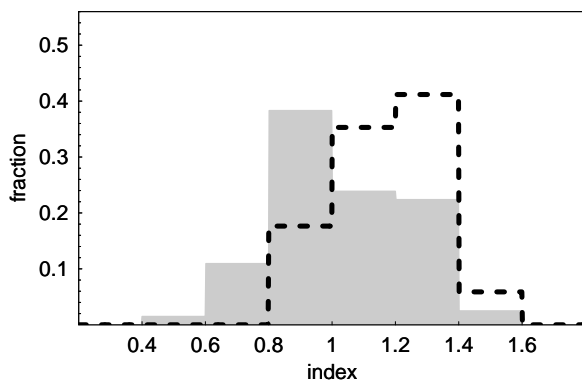
The identification of BLL counterparts of the EGRET sources is a nontrivial task and becomes sometimes a subject of debates. There exist EGRET sources identified with BLLs by one authors but identified with other objects (e.g. clusters of galaxies) by others. For this study, we select all potential BLL identifications from Hartman et al. (1999); Mattox, Hartman & Reimer (2001); Gorbunov et al. (2002) and divided them into “high-probability” and “others” following the identification probabilities from Mattox, Hartman & Reimer (2001) (the high-probability subsample includes objects from Tables 1 and 2 of Mattox, Hartman & Reimer (2001)).

In Fig. 1, we present magnitudes and spectral indices of those BLLs in our sample which are associated with catalogued EGRET sources. Fig. 2 compares the distribution of the spectral indices of correlated objects with that of all objects in the sample. In agreement with the two-bump synchrotron-self-Compton SED model, EGRET-selected sources are low-energy peaked. To quantify this statement, we compared the distribution of  $\alpha_{\text{OX}}$  for the EGRET BLLs and that for all objects in the sample by means of the Kolmogorov-Smirnov (KS) test. The probability that the parent distribution is the same is  $P \approx 5 \cdot 10^{-3}$ ; it reduces to  $\approx 10^{-2}$  if only high-probability identifications are used or if the BLLs with potentially strong contribution

<sup>1</sup> Of our sample, 34 objects are not included in the catalog of Chen, Fu & Gao (2005). We assume that the lack of infrared identification implies negligible contribution of the host galaxy for these sources.



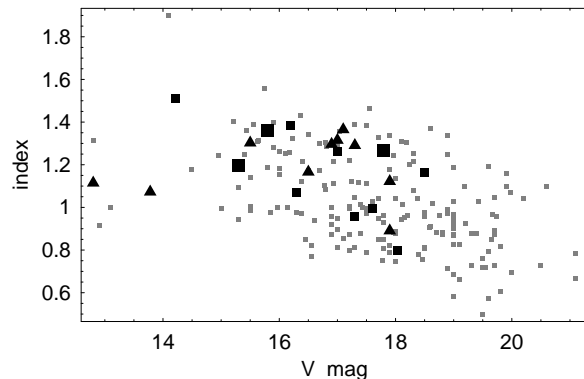
**Figure 1.** Optical-to-X-ray spectral index  $\alpha_{OX}$  versus  $V$ -band magnitude for all BLLs in the sample (gray) and for EGRET-detected objects (black). Black boxes correspond to probable identifications (according to Mattox, Hartman & Reimer (2001)), triangles correspond to less probable or not studied by Mattox, Hartman & Reimer (2001) objects.



**Figure 2.** Distribution of  $\alpha_{OX}$  for all BLLs in the sample (gray) and for objects possibly detected by EGRET (dashed).

of the host galaxy are dropped. The change in the KS probability corresponds to the decrease of the sample size. We note that all 14 high-probability EGRET identifications correspond to BLLs without significant expected contribution from the host galaxy, so a more detailed account of this bias, would it be possible, may only strengthen our conclusion.

A similar study for the BLLs detected at very high energies ( $E \gtrsim 200$  GeV) is hardly possible because they<sup>2</sup> are not drawn from a full-sky survey but from pointed observations of X-ray selected objects (low  $\alpha_{OX}$ ). One should note however that strong X-ray flux does not guarantee that a BLL is a TeV emitter; indeed MAGIC performed a dedicated search for TeV emission from X-ray selected blazars and in many cases did not discover it (Albert et al. 2007). We note in passing that no significant preference in  $\alpha_{OX}$  is found for the BLLs which are possible emitters of 10-GeV gamma-rays (Gorbunov et al. 2005a); they have, on average, intermediate values of  $\alpha_{OX}$  between EGRET and TeV emitters.



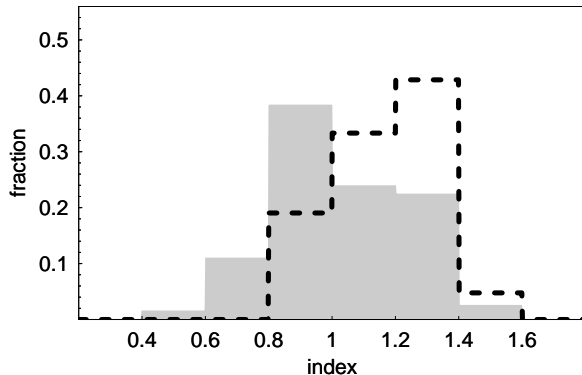
**Figure 3.** Optical-to-X-ray spectral index  $\alpha_{OX}$  versus  $V$ -band magnitude for all BLLs in the sample (gray) and for those correlated with arrival directions of ultra-high-energy cosmic rays (black). Black boxes denote objects correlated with AGASA and Yakutsk cosmic rays (large boxes correspond to objects correlated with doublets), triangles denote objects correlated with HiRes cosmic rays (see text for more details).

#### 4 COSMIC-RAY CORRELATION

Previous studies reported significant correlation between various samples of BLLs from the Véron catalog and various samples of UHECRs. Some of the studies (Tinyakov & Tkachev 2002; Gorbunov et al. 2002) used reconstruction of the arrival directions in the Galactic magnetic field assuming charged cosmic-ray particles; we will not discuss them here because of the ambiguity in the magnetic-field models (see e.g. Cao et al. (2007)). On the other hand, a number of studies suggest correlation which assumes zero deflection (neutral particles); these results are less model-dependent and much more intriguing because neutral UHE particles from BLLs would challenge conventional models of cosmic-ray physics. These claims include the correlation found in the sample of cosmic rays observed by the Akeno Giant Air-Shower Array (AGASA; sample with estimated primary energies  $E > 4.8 \cdot 10^{19}$  eV) and the Yakutsk Extensive Air Shower Array (Yakutsk;  $E > 2.4 \cdot 10^{19}$  eV) detectors where an excess of pairs ‘BLL – cosmic ray’ was seen at separations less than  $2.5^\circ$  (Tinyakov & Tkachev 2001) and in a sample of events with  $E > 10^{19}$  eV observed by the High Resolution Fly’s Eye detector (HiRes) for separations less than  $0.8^\circ$  (Gorbunov et al. 2004). In both cases the separation was consistent with the detector’s angular resolution (which was much better in HiRes than in AGASA and Yakutsk). The correlation with the HiRes sample was confirmed in an unbinned study and was found to be held at lower energies using unpublished data (Abbasi et al. 2006). The probability to observe the correlation with three independent experiments by chance was estimated by Gorbunov & Troitsky (2005) as  $3 \cdot 10^{-5}$  by a Monte-Carlo study which took into account statistical penalty for multiple tries (various catalogs of potential sources tested for correlation).

In Fig. 3, we present magnitudes and spectral indices of those BLLs in our sample which are located within  $2.5^\circ$  of the arrival directions of AGASA and Yakutsk cosmic rays of the sample used in Tinyakov & Tkachev (2001) and within  $0.8^\circ$  of those of the HiRes sample used in Gorbunov et al. (2004). Fig. 4 compares the distribution of the spectral in-

<sup>2</sup> The list of these sources may be found on the MAGIC webpage <http://www.mppmu.mpg.de/~rwagner/sources/index.html>



**Figure 4.** Distribution of  $\alpha_{\text{OX}}$  for all BLLs in the sample (gray) and for objects correlated with ultra-high-energy cosmic rays (dashed).

dices of correlated objects with that of all objects in the sample. We see that the correlation is dominated by low-energy peaked BLLs; the KS test for the two distributions gives  $P \approx 4 \cdot 10^{-3}$ . This confirms and improves our preliminary approximate results (Gorbunov et al. 2005b) based on a sample of BLLs with X-ray identifications ‘by eye’. The results of the present study (cf. Fig. 2 and Fig. 4) support also the association between UHECR and EGRET sources suggested by Gorbunov et al. (2002). This association is not surprising since both acceleration and propagation of UHECR are inevitably accompanied by emission of secondary energetic photons which in turn interact with the cosmic background radiation and lose their energy until it reaches  $\sim 0.1 \div 10$  GeV.

The discussion of the potential bias due to host galaxies is very similar to the case of the EGRET sources. Restriction of the sample to objects with no expected host galaxy contribution results in the KS probability of  $P \approx 10^{-2}$ , change being consistent with the decrease of the sample size. Of 21 objects in the sample associated with UHECRs, only 3 may be affected by the host galaxy, according to Chen, Fu & Gao (2005). This fact is in agreement with previous observations (Tinyakov & Tkachev 2001) that the UHECR correlation is stronger for objects with unknown redshifts.

The correlation between BLLs and UHECRs seen in HiRes data (Gorbunov et al. 2004) has been tested recently by the Pierre Auger (PA) Collaboration (Harari et al. 2007); no positive signal was found. This is not conclusive however for the following reasons. Firstly, PA is located in the Southern hemisphere and sees different BLLs than other experiments; moreover, due to incompleteness of the catalogs, the number of potential UHECR emitters is much less in the South. For instance, of 99 objects in our sample which have  $\alpha_{\text{OX}} > 1$  (which seem to correlate with UHECR stronger, see Fig. 4), 82 can be seen by HiRes but only 46 are in the field of view of PA, most of them only at large zenith angles and for a small fraction of time. The ‘factor of merit’ depends also on the angular resolution of the experiment which is twice worse in the PA surface detector than in HiRes (stereoscopic mode). This problem was quantified by Gorbunov et al. (2006) where it has been shown that to reach the HiRes sensitivity for the signal found by Gorbunov et al. (2004) in the set of 271 events, PA has to accumulate  $\sim 3500$  events in the same energy range. We

note that Harari et al. (2007) used 1672 events for the test of this signal.

Secondly, as it has been pointed out by Gorbunov et al. (2004) and Abbasi et al. (2006) and further discussed by Tinyakov & Tkachev (2006), the correlation observed by HiRes implies neutral cosmic particles travelling for cosmological distances, the fact which requires unconventional physics. Most probably the primary particles of the resulting air showers are neither protons, nor nuclei. However, the energy determination of the PA surface detector is extremely sensitive to the type of the primary cosmic particle because of very strong sensitivity of water tanks to muons in the air shower. For instance, energies of gamma rays are always underestimated by a factor of a few (see e.g. Billoir, Roucelle & Hamilton (2007)). Due to the steeply falling spectrum of UHECRs, this may dilute the observed signal. PA possesses fluorescent detectors similar to those of HiRes, but the BLL correlation was never tested with them. Future tests of the correlation should be performed with high-resolution fluorescent detectors, preferably in the Northern hemisphere, the Telescope Array (see e.g. Martens et al. (2007)) providing a good example.

## 5 CONCLUSIONS

We have studied the distribution of broadband optical-to-X-ray spectral indices  $\alpha_{\text{OX}}$  of 201 confirmed BLLs from the Véron catalog which have at least 68% confident X-ray identification in the Quasars.org catalog. In accordance with the synchrotron-self-Compton two-bump SED models, a subsample of EGRET-detected BLLs has on average high  $\alpha_{\text{OX}}$  (sources are strong in optical but relatively faint in X rays). One of the most important results of the study relates to the BLLs correlated with ultra-high-energy cosmic rays: most of them are low-energy peaked. Both for the EGRET and UHECR associations, the contribution of the host galaxy is expected to be negligible according to the infrared photometry of Chen, Fu & Gao (2005). This fact agrees well with the expectations that the EGRET sample is dominated by beamed sources and that the UHECR sources are powerful and possess strongly collimated jets pointing precisely to the observer. The present study narrows the class of potential UHECR emitters to those with high  $\alpha_{\text{OX}}$ . This fact may be used for further tests of BLL – cosmic ray correlation with fluorescent detectors and may shed light on the origin of the correlated cosmic-ray particles. If confirmed, this correlation would point to completely new phenomena in particle physics or/and astrophysics because no known neutral particles of these energies are expected to travel for distances larger than  $\sim 10$  Mpc.

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